

Biomechanics of the Normal and Abnormal Foot

KEVIN A. KIRBY, DPM, MS*

The foot is an engineering marvel that allows the body to perform many physical activities over a wide variety of terrain with remarkable efficiency. The functions of the foot and the lower extremity are biomechanically integrated; thus normal lower-extremity function requires normal foot function and *vice versa*. Because the subtalar joint is the main pedal joint allowing the triplanar translation of motion between the foot and lower extremity, normal subtalar joint function is critical to normal foot and lower-extremity function. This article provides an overview of the interrelationships between foot and lower-extremity function and mechanically based pathology of the foot and lower extremity, with an emphasis on the subtalar joint. (J Am Podiatr Med Assoc 90(1): 30-34, 2000)

The human foot is an engineering marvel. It is designed to allow a bipedal animal, the human, to walk, run, and jump efficiently over many types of supporting surfaces without pain or injury. It is subjected to impact forces from contact with the ground and must therefore be able to work with the rest of the body to absorb or dissipate the stresses on the structural components of the foot and lower extremity. The foot is also subjected to large magnitudes of rotational forces—or moments—during weightbearing activities. It must be able to handle the moments that result from ground-reactive force in such a way that the joints of the foot and lower extremity accelerate and decelerate smoothly and efficiently during the activity being performed. Because the foot, lower extremity, and rest of the body must all function in concert during weightbearing activities, the lower extremity and body will not function normally if the foot does not also function normally. Furthermore, the foot must remain functional for the lifetime of the individual, or pain or disability will result.

The Normal Foot

Nearly 3 decades ago, Root et al¹ published their "Biophysical Criteria for Normalcy," which listed eight cri-

* Assistant Clinical Professor, Department of Podiatric Biomechanics, California College of Podiatric Medicine. *Mailing address:* 2626 N St, Sacramento, CA 95816.

teria representing the ideal structure for the foot and lower extremity. For many years, podiatric physicians have been taught that the structure of an individual's foot and lower extremity must meet all eight of these criteria in order to be considered "normal."

Unfortunately, very few individuals have feet and lower extremities that can be considered "normal" under the relatively strict definition proposed by Root et al.¹ As the criteria for normalcy established by Root et al are too restrictive to be practical for this discussion, the author will define the normal foot and lower extremity as those that function normally during gait, have no history of significant trauma or surgery, and currently have no pain or significant deformity.

Normal and Abnormal Function of the Foot During Standing

During bipedal standing, each foot supports approximately one-half of the individual's body weight. In order for the body to maintain balance in bipedal standing, a plumb line dropped from a person's center of mass must fall within an imaginary area that lies under or between the feet. The individual uses the muscles of the lower extremity to maintain balance by applying varying magnitudes of force on the ground with the plantar aspect of the foot to adjust for any tendencies for the center of mass to migrate outside the balance area between the two feet.²⁵

In a normal foot during bipedal standing, the gastrocnemius muscle is intermittently active to maintain the center of mass somewhat anterior to the ankle joint axis (Fig. 1). This muscle exerts a plantarflexion moment across the ankle joint axis to counteract the dorsiflexion moment from the center of mass being positioned anterior to the ankle joint axis. Individuals with normal feet will also intermittently contract the other extrinsic muscles of the foot in order to maintain their center of mass in the balance area between their feet.^{5,6}

A foot that functions the most normally during walking does not exhibit a neutral position of the subtalar joint during bipedal standing. In 15 years of clinical observations, the author has noted that feet that are in the subtalar joint neutral position during standing are likely to exhibit symptoms or be associated with clinical findings indicating the presence of an abnormal supination moment acting across the subtalar joint axis. The author also considers feet that have the subtalar joint either in or within 1° to 2° of the maximally pronated position during standing to be abnormal owing to the lack of available prona-

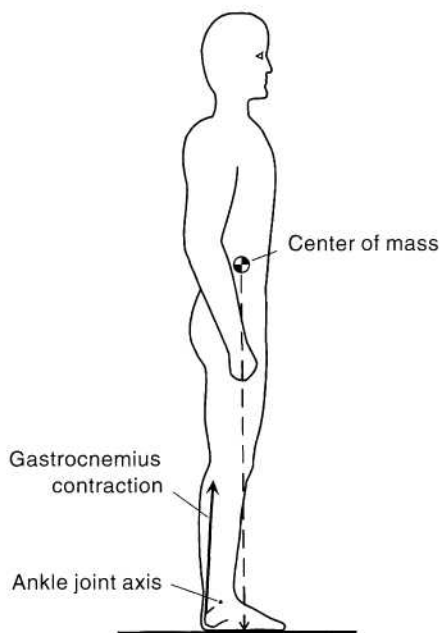


Figure 1. Normal relaxed bipedal stance. The center of mass of the body is positioned anterior to the ankle joint axis, which causes a dorsiflexion moment across the ankle joint axis. In order for the body to maintain equilibrium across the ankle joint axis and stay balanced while in this position, the gastrocnemius muscle must contract to exert a plantarflexion moment across the ankle joint axis.

tion range of motion for shock absorption. The feet that the author has observed to function the most normally during gait have subtalar joints that are approximately midway between the maximally pronated and neutral positions.

In order for the subtalar joint to be maintained approximately midway between the neutral position and the maximally pronated position, there must be a balance of pronation and supination moments acting across the subtalar joint axis. Whenever there are equal magnitudes of pronation and supination moments acting across the subtalar joint axis during standing, rotational equilibrium of the subtalar joint exists.⁷ Rotational equilibrium occurs across an axis of rotation only when the sums of the moments acting in both directions of rotation are exactly equal to each other.⁸ The most common example of rotational equilibrium in the subtalar joint is the relaxed calcaneal stance position, in which the subtalar joint is in a static position, with no rotational velocity.⁷

The author has clinically measured the location of the subtalar joint axis in relation to the plantar aspect of the foot in well over a thousand normal and abnormal feet. It is apparent from these observations that the position of the subtalar joint axis in relation to the plantar weightbearing surface of the foot is of prime importance in determining the balance of supination and pronation moments acting across the subtalar joint in standing and other weightbearing activities.^{7, ^}

During relaxed bipedal standing, the subtalar joint axis of a normal foot exits through the posterosuperolateral aspect of the calcaneus posteriorly and lies approximately over the first metatarsal head area anteriorly (Fig. 2). With the subtalar joint axis in this positional relationship to the plantar aspect of the foot, the ground-reactive force acting on the medial calcaneal tubercle causes a supination moment across the subtalar joint axis, and the ground-reactive force acting on the lateral midfoot and lateral metatarsal heads causes a pronation moment across the subtalar joint axis. In addition, muscular tension and ligamentous tension on the bones of the foot cause supination and pronation moments across the subtalar joint. A normal foot will have a balance of these pronation and supination moments acting across the subtalar joint axis during standing so that the subtalar joint is resting approximately midway between the neutral and the maximally pronated position of the subtalar joint axis.^{7,9,13}

Any number of structural deformities can cause medial deviation of the subtalar joint axis; in medial deviation, the subtalar joint axis is medially translated or internally rotated compared with the normal subtalar joint axis location (Fig. 2). As a result, the

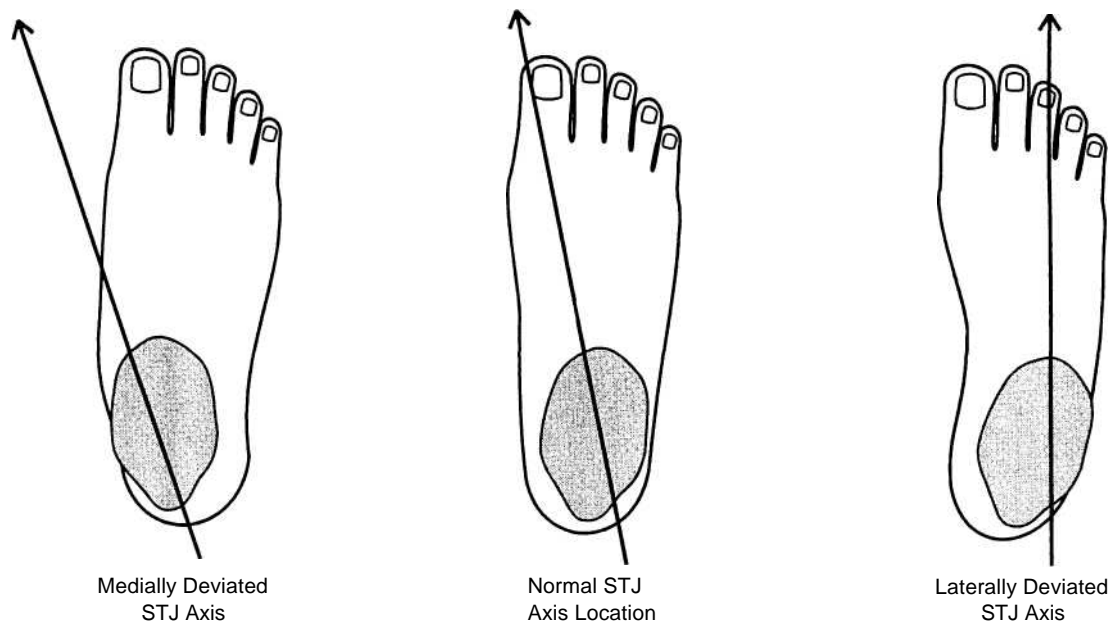


Figure 2. When the subtalar joint (STJ) axis is in its normal position (center), it passes through the posterolateral aspect of the calcaneus and anteriorly over the first metatarsal head. When it is medially deviated (left), there are excessive pronation moments acting across it. When it is laterally deviated (right), there are excessive supination moments acting across it. The position of the STJ axis in relation to the plantar aspect of the foot is an important determinant of the function of the foot during standing, walking, and other weightbearing activities.

pronation moments are increased and the supination moments are decreased by the action of ground-reactive force on the plantar structures of the foot and by the actions of ligamentous and muscular tension on the bones of the foot. A foot with a medially deviated subtalar joint axis is likely to be maximally pronated at the subtalar joint during both standing and other weightbearing activities owing to the increase in pronation moments and the decrease in supination moments acting across the subtalar joint axis.^{7,913}

Lateral deviation of the subtalar joint axis is caused by structural deformities in which the subtalar joint axis is laterally translated or externally rotated compared with the normal subtalar joint axis location (Fig. 2). In a foot with a laterally deviated subtalar joint axis, the pronation moments are decreased and the supination moments are increased; this results in a net increase in supination moment.^{7,913}

These subtle but measurable changes in spatial location of the subtalar joint axis in relation to the plantar aspect of the foot cause most foot and lower-extremity biomechanical pathology seen in cases of abnormal feet.^{7,913} Positional changes of as little as 2 mm in the subtalar joint axis location in relation to the plantar aspect of the foot may alter the balance of moments acting across the subtalar joint axis so

significantly that a normal foot may begin to function abnormally and develop biomechanical pathology.

Normal and Abnormal Function of the Foot During Walking

During walking, the foot functions as the base of an inverted pendulum where the body's center of mass is transferred from posterior to anterior over the stationary foot.² This process is repeated for the contralateral foot and then repeated over and over again during gait. Because the most energy-efficient method of moving a body from one point to another is to move its center of mass along as straight a line as possible with as constant a velocity as possible, the foot must allow for this smooth transfer of the center of mass over the stationary foot. In this way, energy is conserved, and the work associated with walking is kept to a minimum.⁸

In addition to facilitating the relatively smooth transfer of the center of mass from one point to another, the foot also acts as a terrain adapter, a shock absorber, and a rigid lever during walking. Initially, during the contact and early midstance phases, the subtalar joint pronates. The increased range of motion of the midtarsal and intertarsal joints occurring

with subtalar joint pronation allows the foot to adapt to uneven terrain.¹² In addition, subtalar joint pronation allows for shock absorption. The linearly directed momentum of the body striking the ground at heel strike is converted into an angular momentum (ie, internal rotation) of the whole lower extremity. The ability of subtalar joint pronation to act as a "momentum converter" during the contact phase of walking is critical in dissipating the shock of impact on the structural components of the body. Inadequate subtalar joint pronation during the contact phase commonly leads to impact-related injury or dysfunction.¹³

During the late midstance phase of walking in the normal foot, as the center of mass is now moving ahead of the stationary foot, the tibia, femur, and pelvis should all be externally rotating in relation to the ground; this allows the contralateral limb to advance smoothly ahead of the stance phase limb. In order for the necessary external rotation of the lower extremity to occur during late midstance, either the foot must slide in an external rotation direction in relation to the ground or the subtalar joint must supinate.^{5, 14, 16} Either inadequate supination motion or pronation motion of the subtalar joint during late midstance will lead to the common gait finding of abductory twist at the instant of heel lift. In addition, the abnormal gait finding of late midstance pronation of the subtalar joint is probably responsible for many biomechanically induced pathologies such as plantar fasciitis, intermetatarsal neuroma, hallux limitus, hallux valgus, sesamoiditis, and low-back pain.¹³

After heel lift in a normal foot, the subtalar joint should be supinating because of the subtalar joint supination moment generated by contraction of the gastrocnemius and soleus muscles.^{5, 14, 16} Supination motion of the subtalar joint causes the talar head to rotate externally and translate in a superolateral direction in relation to the anterior calcaneus; this, in turn, results in the talonavicular joint being positioned more superiorly and less medially in relation to the calcaneocuboid joint. The more vertical alignment of the talonavicular joint to the calcaneocuboid joint, which results directly from subtalar joint supination, gives the foot a greater structural potential to resist the powerful dorsiflexion moments that occur across the midtarsal joint as a result of ground-reactive force acting on the plantar metatarsal heads during propulsion. Therefore, the foot becomes a more rigid and efficient lever as a direct result of positional changes of the midtarsal joint caused by closed-kinetic-chain subtalar joint supination.^{5, 16, 17}

If subtalar joint supination does not occur during propulsion, the extrinsic and intrinsic muscles of the foot must contract more forcefully to prevent the

forefoot from excessively dorsiflexing on the rear-foot. If the midtarsal or intertarsal joints are unstable owing to subtalar joint pronation, propulsion by the lower extremity will be relatively inefficient, as the foot may be unable to generate sustained plantar force on the ground without experiencing wasted motion at these joints.⁵

Detailed kinematic and kinetic analysis of the human body during walking reveals an amazing series of carefully orchestrated events that allows an individual to move efficiently from one point to another with a minimum of energy. Of utmost importance is the proper timing and appropriate movements of the foot in relation to the ground and the lower extremity. A thorough analysis of walking biomechanics clearly demonstrates that without normal foot function, the rest of the lower extremity and body cannot possibly function normally during walking. Therefore, those health practitioners with the greatest knowledge of the intricate biomechanics of the foot and lower extremity will be the most successful in treating the multitude of mechanically related foot and lower-extremity pathologies that can occur.

References

1. ROOT ML, ORIEN WP, WEED JH, ET AL: *Biomechanical Examination of the Foot*, Vol 1, Clinical Biomechanics Corp, Los Angeles, 1971.
2. WINTER DA: *A.B.C. (Anatomy, Biomechanics and Control) of Balance During Standing and Walking*, Waterloo Biomechanics, Waterloo, Ontario, Canada, 1995.
3. LEVEAU BF: *Williams and Lissner's Biomechanics of Human Motion*, 3rd Ed, WB Saunders, Philadelphia, 1992.
4. HICKS JH: "The Three Weight-Bearing Mechanisms of the Foot," in *Biomechanical Studies of the Musculo-Skeletal System*, ed by FG Evans, Charles C Thomas, p 161, Springfield, IL, 1961.
5. ROOT ML, ORIEN WP, WEED JH: *Normal and Abnormal Function of the Foot*, Clinical Biomechanics Corp, Los Angeles, 1977.
6. BASMAJIAN JV, BENTZON JW: An electromyographic study of certain muscles of the leg and foot in the standing position. *Surg Gynecol Obstet* 98: 666, 1954.
7. KIRBY KA: Rotational equilibrium across the subtalar joint axis. *JAPMA* 79: 1, 1989.
8. OZKAYA N, NORDIN M: *Fundamentals of Biomechanics: Equilibrium, Motion and Deformation*, Van Nostrand Reinhold, New York, 1991.
9. KIRBY KA: Methods for determination of positional variations in the subtalar joint axis. *JAPMA* 77: 228, 1987.
10. KIRBY KA, LOENDORF AJ, GREGORIO R: Anterior axial projection of the foot. *JAPMA* 78: 159, 1988.
11. KIRBY KA, GREEN DR: "Evaluation and Nonoperative Management of Pes Valgus," in *Foot and Ankle Disorders in Children*, ed by S DeValentine, p 295, Churchill Livingstone, New York, 1992.
12. KIRBY KA: The medial heel skive technique: improving

- pronation control in foot orthoses. JAPMA 82: 177, 1992.
13. KIRBY KA: *Foot and Lower Extremity Biomechanics: A Ten Year Collection of Precision Intricast Newsletters*, Precision Intricast, Payson, AZ, 1997.
 14. WRIGHT DG, DESAI SM, HENDERSON WH: Action of the subtalar and ankle joint complex during the stance phase of walking. J Bone Joint Surg Am 46: 361, 1964.
 15. LEVENS AS, INMAN VT, BLOSSER JA: Transverse rotation of the segments of the lower extremity in locomotion. J Bone Joint Surg Am 30: 859, 1948. INMAN VT,
 16. RALSTON HJ, TODD F: *Human Walking*, Williams & Wilkins, Baltimore, 1981.
 17. ELFTMAN H: The transverse tarsal joint and its control. Clin Orthop 16: 41, 1960.

-
- YES, I want the podiatric profession to perpetuate.**
 - YES, I want student indebtedness to end.**
 - YES, I want scholarship funding to increase.**

*If you checked any of the above,
we need one more check.*

The Fund for Podiatric Medical Education is dedicated to the financial support of students of podiatric medicine in order to foster and enhance the growth and stability of the profession and further improve the foot health of the nation.

Please help by calling **301-571-9200**.

That way, you can do more than just wish for changes.
You can bring us one step closer to making these a reality.
With your help, there is hope.



9312 Old Georgetown Road • Bethesda, Maryland 20814
